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Simultaneous High Speed Schlieren and Direct Imaging of Ignition Process with Digitally Enhanced Visualisation

Yiran Wang[a], Yang Zhang[a]*

[a]*Department of Mechanical Engineering, The University of Sheffield, Sheffield, S1 3JD, UK*

Abstract

In this paper, a combined method of schlieren and digital colour image processing is developed to study the effect of ignition location on the propagation of propane diffusion flames. The early weak blue flame is visualised through selective digital imaging enhancement techniques, which have revealed that a typical orange diffusion flame is often formed inside a blue flame pocket at the beginning of the ignition when ignited at the centreline of the fuel jet. When the ignition location towards the out edge of the fuel/air mixing boundary, the orange flame shifted and gradually broke the blue flame pocket. In the meantime, the flame was observed to propagate faster. The ratio of orange flame areas rose and the blue flame area fell accordingly.

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Keywords:Digital image superposition,Schlieren,Digital imaging enhancement, Ignition

1. Introduction

Digital imaging techniques have been intensively utilised in the investigation of combustion science due to high efficiency, non-intrusiveness and reasonable cost. High speed schlieren imaging enables the visualisation of the hot gas dynamics and air/fuel mixing. The other characteristic properties, such as flame colour and flame temperature can be resolved by high speed colour imaging techniques. Wang et al [1] applied both colour and schlieren imaging techniques to investigate flame ignition process, which revealed that the initial flame kernel was very sensitive to the ignition location. At present, these two techniques are often employed and analysed independently. Thus it will be helpful to apply the synchronised schlieren and colour imaging techniques for the better visualisation of the hot gas movement, fuel/air mixing and flame colour distribution. The weak blue flame (towards green band due to higher C_2*if it is fuel rich) under premixed and non-premixed flame conditions is known to be hard to visualise, especially in the presence of the orange flame. Huang and Zhang [2,3] applied HSV colour model and used the hue value to identify the blue and green flame pixels, which can then be selectively

* Corresponding author. Tel.: +44 1142227880
E-mail address: yz100@sheffield.ac.uk

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enhanced by digital image processing before recombining with the other colour pixels to provide a much improved whole flame pattern.

Previous research indicated that the ignition location was a key factor affecting flame dynamics [4,5]. However, the effect of ignition location on the colour distribution has seldom been analysed. In this work, the ignition of a turbulent diffusion flame is studied using two synchronised high speed cameras with one for schlieren and the other for direct colour imaging. The relationship between the flame colour distribution of flame patterns and ignition locations is visualised and analysed.

2. Experimental setup

The schematic of the experimental setup is shown in Figure 1. A standard Z-type schlieren structure was constructed from a pair of $\lambda/10$, 0.3048 m diameter and 3.048 m focal length parabolic mirrors. The flame ignition process was captured by a high speed camera A (Photron FASTCAM SA4) with a resolution of 1024 by 1024 pixels, which was set as 1000 frame rate and 1/30000 shutter speed under the schlieren system. The colour images were captured by camera B with 1000 frame rate and 1/2000 shutter speed. The two cameras were synchronised and controlled by a trigger. The flow meter regulated the gas flow rate and was controlled by the LabVIEW software. The fuel was injected through a nozzle of 9.6 mm diameter. The ignition location could be changed by adjusting the electrode device, which was placed above the burner and used for ignition, with approximately 30kV output voltage. A pair of steel electrodes was kept 10mm apart from each other. The fuel jet flow rate was set at 5 l/min and 10 l/min, which corresponds a Reynolds number of 2451 and 4902 respectively.

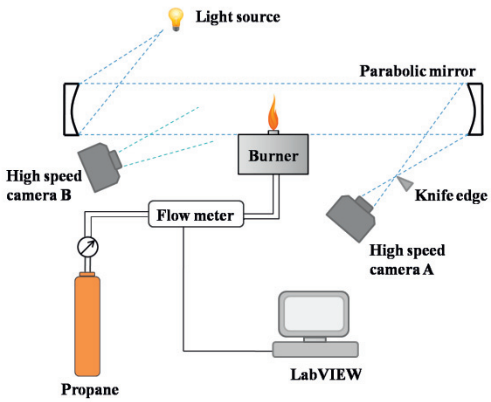


Figure 1. Schematic setup of the experimental system.

3. Results and Discussion

The two synchronised high speed cameras captured the whole ignition process until the flame reaches a steady state. The hot gas movement and flame colour distribution were analysed and visualised with the help of schlieren and colour imaging processing. In the early stage of the ignition, the flame is dominantly blue and the flame emission is weak, which can be enhanced through the DFCD method for better visualisation [2]. The blue and green pixels were identified and enhanced by 25 times in order to visualise the whole flame pattern. Figure 2 shows the comparison between the original flame image and the colour-enhanced image. The result demonstrates that selective image enhancement is essential in obtaining the real combustion process.

According to the experimental results, the ignition process of the 5 l/min and 10 l/min test cases are quite similar. Therefore only the 5 l/min test case results will be presented. It can be seen that a typical orange diffusion flame is formed inside a blue flame pocket at the early stage of the ignition if the flame is ignited at the centreline of the fuel jet (Figure 3). In this situation, the flame was ignited in a fuel-rich condition. The outer layer fuel was ignited under a well mixed fuel-air condition and provided a high temperature blue pocket surrounding the unburned fuel. The hot gas of the combustion products blocked/slowed the air mixing path to the encircled fuel pocket, which contributed the pyrolysis of the propane and generated the carbon soot at the centre. The soot was then burned with the establishment of the orange flame. However, this phenomenon is less obvious when the ignition location is not at the centreline. The local high temperature initiated at the ignition location led to the pyrolysis of the unburned fuel due to better local air/fuel mixing and faster overall heat generation. The orange flame zone from pyrolysis shifted with the ignition location and broke the blue flame pocket (Figure 3).

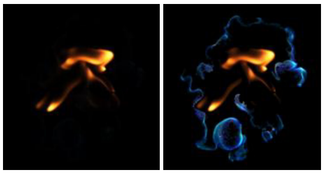


Figure 2.The comparison between the original flame image and specific colour-enhanced image at 0.060s after ignition. The flame was ignited at centreline at 5 l/min fuel flow rate.

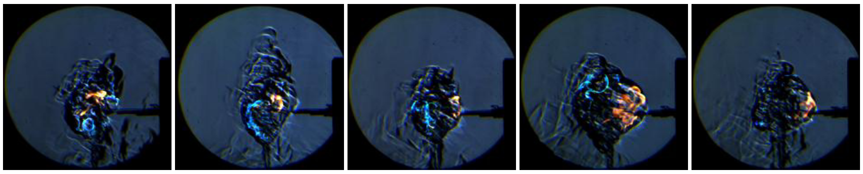
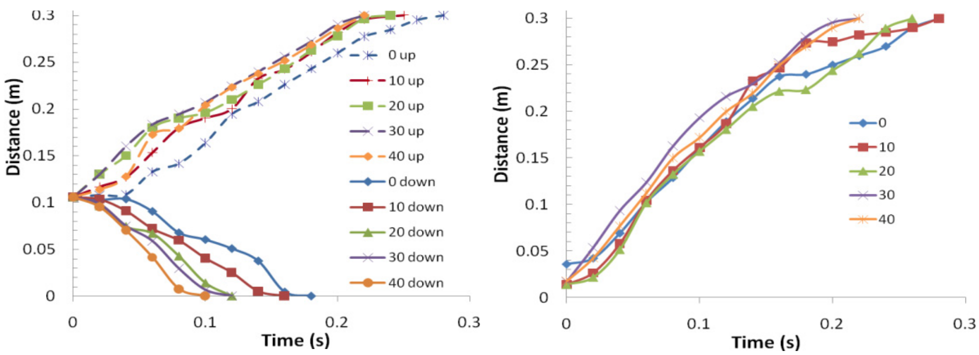


Figure 3. The enhanced colour and schlieren combined images at 0.060s after ignition. The flames were ignited at 0, 10, 20, 30 and 40mm away from the centreline, at 5 l/min fuel flow rate.



(a) (b)

Figure 4 (a) Distance-time graph for upward and downward propagation of flame; **(b)** Distance-time graph for flame horizontal propagation. '0', '10', '20', '30' and '40' indicate the direct distance (in mm) from the ignition points to centerline. 'Up' and 'down' indicate the direction of flame propagation.

The fuel-air mixing boundary can be visualised by schlieren imaging. At a height of 100mm over the nozzle the visible fuel air boundary edge is observed nearly 40mm away from the centreline. From Fig. 4, it can be seen that the flame propagated faster in both vertical and horizontal directions when the direct distance from the ignition point to the centreline of the fuel jet was increased. When the ignition location approached the fuel/air mixing boundary, the fuel and air were well mixed and promoted the flame propagation speed. The mean standard deviation of the data from each case under the same flow condition is less than 5%, which indicates good experimental repeatability. The superposed image sequence of schlieren and direct flame colour imaging in Fig. 5 demonstrates how the ratio of the orange flame areas increased when the ignition location approached out edge of the mixing boundary. At the same time, the ratio of the blue flame area is reduced. When the fuel was ignited near the centreline, the flame propagated slowly and generated less heat at the beginning of ignition. After a period of time, the flame propagated outwards. The fuel and air were well mixed at the outer layer, thus the fuel was burnt faster and established the blue flame. The high temperature from the combustion product promoted the pyrolysis of propane gas fuel; hence, the ratio of the orange flame zone rose and that of the blue flame zone fell.

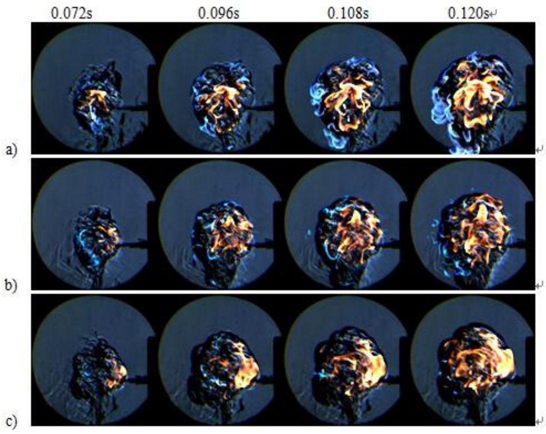


Figure 5(a), (b) and (c) Combined images sequence when the flame is ignited 0, 20 and 40mm away from the centerline, at 5 l/min fuel flow rate.

4. Conclusion

The effect of ignition location on a propane diffusion flame was investigated by digital superposition which combines the simultaneously taken schlieren and colour-enhanced images. It was found that a typical orange diffusion flame is often formed inside a blue flame pocket at the beginning when ignited at the centreline of the fuel jet. The combustion product blocked the mixing of fuel and air, and promoted the pyrolysis of fuel. Then the carbon soot generated from pyrolysis was burned as an orange flame inside the blue flame pocket. When the ignition location approached the out edge of the fuel/air mixing boundary, the orange flame zone shifted with the ignition location and gradually broke the blue pocket. In the meantime, the ratio of orange flame areas rose, and the ratio of the blue flame areas reduced accordingly. This can be explained as resulting from initial combustion producing a local high temperature at the ignition location, with the flame produced propagating faster (i.e. higher overall heat generation) near the out mixing boundary, which leads to more pyrolysis of unburned fuel and therefore the higher proportion of orange flame zone generated.

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